

# Reduction of Aircraft Tyre Wear by Pre-rotating Wheel using ANSYS Mechanical Transient

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**keywords:** aircraft touchdown, aircraft tyre wear, pre-spinning wheels, Archard theory, ANSYS transient.

**Abstract:** Heavy aircraft main landing gear tyres skid immediately after touchdown as result of the high slip ratio between the tyres and runway, which lead to tyre wear and smoke. In this paper, the tyre wear is modelled on the Archard theory using ANSYS mechanical transient, to reveal the wheel's dynamic and the tyre tread wear. The wheel's dynamic and the amount of wear are calculated for initially static and for pre-spun wheels in order to find the effectiveness of the technique of pre-spinning the wheel, as suggested by many patents since the early days of airplane use, in order to eliminate aircraft landing wear and smoke.

## Introduction

The heavy aircraft typical landing requires a high approach speed relative to its weight limitation to avoid a high sink rate [1]. This leads to a high slip ratio between the main landing gears wheels and runway as the tyres touchdown with zero rotational speed. At landing impact, tyre sliding occurs and then it spins-up to reach aircraft forward speed. High tyre slip generates heat, which is enough to melt a layer of the tread rubber. Melted rubber became weak as its material bonds linkage is broken when the critical temperature is exceeded [2]. One-third of the eroded rubber burnt off under the skidding tyre vaporizes in the form of smoke, while the remaining eroded rubber adheres to the runway [3]. However, the tyre temperature rises up as slip increases. Therefore, the skidding wheel distance and time are major factors of tyre wear and smoke [4]. However, wear is a complex phenomenon; and it is difficult to get the exact value [5]. The Archard wear theory is a simple and common model used to calculate sliding wear between two bodies and it is chosen by ANSYS [6, 7]. The Archard formula considers the main parameters: the reaction force acting on the tyre contact patch, slip distance, contact surface, and environmental conditions such as temperature, hygrometry, and atmospheric composition [8].

Bennett, M., et al., (2011) studied the smoke generated by aircraft landing using optical and condensation particle counters plus a scanning Lidar system [3]. The researchers showed the total rubber lost from Boeing 747 main landing gear tyres per landing to be up to 1 kg.

Multiple studies were found to have simulated aircraft wheel dynamics at landing impact. A Boeing 747-400 main landing gear “shimmy” oscillation has been modeled by Besselink (2000) [9]. The wheel spun-up from zero rotation to free rolling within 0.1 seconds, which agreed with Khapane (2006), who modeled the aircraft wheel dynamic at touchdown [10].

Padovan, Kazempour and Kim (1991) modeled the energy balance of a single wheel of the space-shuttle. In this study, interfacial friction between the tyre and runway work rate was computed and the spin-up time was estimated to be in a range of 0.1 to 0.24 depending on the constant friction coefficient of 0.7 and 0.3 respectively. After various simulations, they concluded that the tyre wear increased in line with an increase of surface friction coefficients, the horizontal landing speed and the sink rate [11].

In this paper, a case study of a Boeing 747-400 single main landing gear wheel is modeled using ANSYS to estimate the amount of tyre wear immediately after touchdown for static and pre-spinning wheels; and is based on the Archard wear theory. The model provides results for tyre tread wear, skidding distance and time for a typical aircraft landing, and for wheels already rotated before touchdown, to check how much reduction of tyre wear can be achieved by pre-spinning the wheel, as suggested by many patents [12-14]. The results are expected to be highly accurate as ANSYS provides results which are very close to those in real operating conditions. Moreover, the input data includes assumptions that are used for all simulations are similar in order to get a fair comparison of results.

## Modeling and Simulation

The technique used in a typical aircraft approach is to maintain a constant speed until about 15m above the runway threshold and then flare to reduce the sink rate for a smooth landing. This manoeuvre increases the aircraft pitch angle to induce drag, which will reduce the landing speed by approximately 10 knots (5.14 m/s) to lessen the landing distance [15]. Fig. 1 shows the aircraft landing process; approach, flare, fully locked and spin-up wheels and deceleration. This model simulates the skidding phase after landing impact. Constant horizontal speed is used, because the pilot will not apply the brake immediately after touchdown to avoid more wheel skidding that leads to increased tyre and brake pad wear [16].

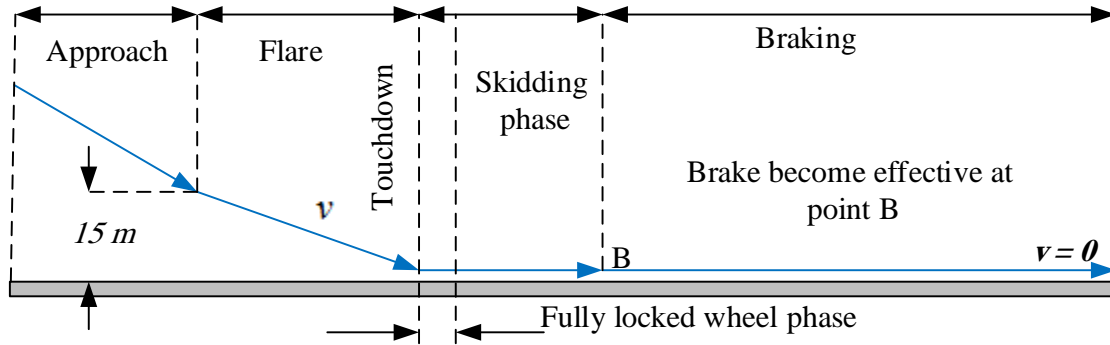


Fig. 1. Typical aircraft flight path (modified from [17])

The sink rate of our aircraft case study is usually in a range of 1.5 m/s to 3 m/s [18]; and the approach speed is 80.78 m/s [19]. For every simulation, a sink rate of 2.5 m/s and a landing speed of 75.6 m/s are used. The sink rate is assumed, while the horizontal touchdown speed is based on the approach speed minus 5.14 m/s from a decrease caused by the flare [15]. The aircraft wing will not produce significant lift force at touchdown, and assuming zero lift allows the calculation of the aircraft's maximum landing weight (MLW) divided by sixteen (16 is the number of the main landing gear wheels) to be valid, as the weight that is applied to a single wheel [20, 21].

**Landing Gear Dynamic:** The vertical and longitudinal forces acting on the tyre contact patch at the moment of touchdown are shown by the mass-spring-system in Fig. 2 [22, 23]. From Fig. 2, the equation of vehicle mass oscillation vertically is:

$$F_y = m\ddot{y} + c\dot{y} + ky \quad (1)$$

where,  $m$  is the vehicle mass applying on the shock absorber (kg),  $\ddot{y}$  is the vertical acceleration of aircraft structure ( $m/s^2$ ),  $c$  is the landing gear shock absorber damping coefficient (Ns/m),  $\dot{y}$  is the aircraft sink rate (m/s),  $k$  is the shock absorber linear stiffness (N/s), and  $y$  is the vertical displacement (m). The reaction force acting on the tyre contact area vertically is:

$$F_R = c\dot{y} + ky \quad (2)$$

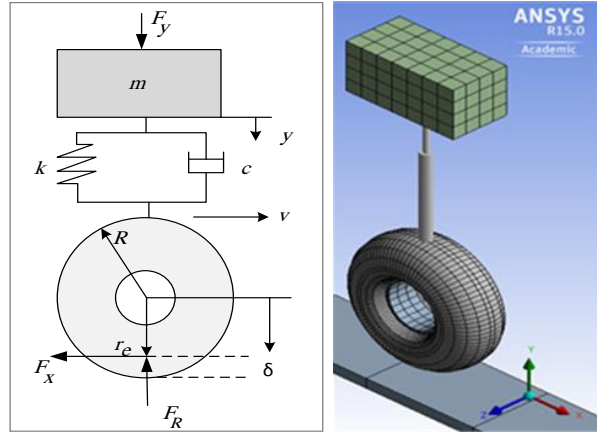


Fig. 2. Mass-spring-damper system(left) modeled by ANSYS (right).

In a static condition, Eq. 1 & Eq. 2 show that the reaction force,  $F_R$  is equal to the total weight applying on the wheel, which also equal the spring displacement multiplied by the spring constant. The longitudinal friction force calculated by simple coulomb friction is:

$$F_X = \mu F_R \quad (3)$$

where,  $\mu$  is the friction coefficient and it is a function of the aircraft's horizontal speed,  $v$ , and wheel slip,  $\lambda$  [24]:

$$\mu(v, \lambda) = \frac{F_x}{F_R} \quad (4)$$

**Wheel Dynamic:** At touchdown, the tyre deflect is effected by a downward vertical force. Therefore, the tyre effective radius should be used which can be calculated for radial tyres as [25]:

$$r_e = R - \frac{\delta}{3} \quad (5)$$

where,  $R$  is the actual wheel radius (m), and  $\delta$  is the amount of tyre deflection (m). From the rotational form of Newton's 2nd law, the wheel's angular acceleration is:

$$\dot{\omega} = \frac{F_x r_e}{I} \quad (6)$$

where,  $I$  represents the wheel's moment of inertia. By integral Eq. 5 with regard to time, the wheel's angular speed will be:

$$\omega = \int \dot{\omega} + \omega_i \quad (7)$$

where,  $\omega$  is the wheel's angular speed (rad/sec), and  $\omega_i$  is initial wheel rotation, which will be zero for the first simulation as was shown to be typical in landing. The wheel slip ratio can be written as:

$$\lambda = \frac{v_r}{v} \quad (8)$$

where,  $v$  is the aircraft's forward speed, and  $v_r$  is the relative speed between the forward speed of the aircraft and a point tangential to the outer tyre surface. The relative speed has two forms depending on whether the wheel is skidding or slipping. Fig. 3 describe four stages of wheel behaviour immediately after touchdown, as it spins up to a free-rolling level resulting in a sudden increase in the friction force.

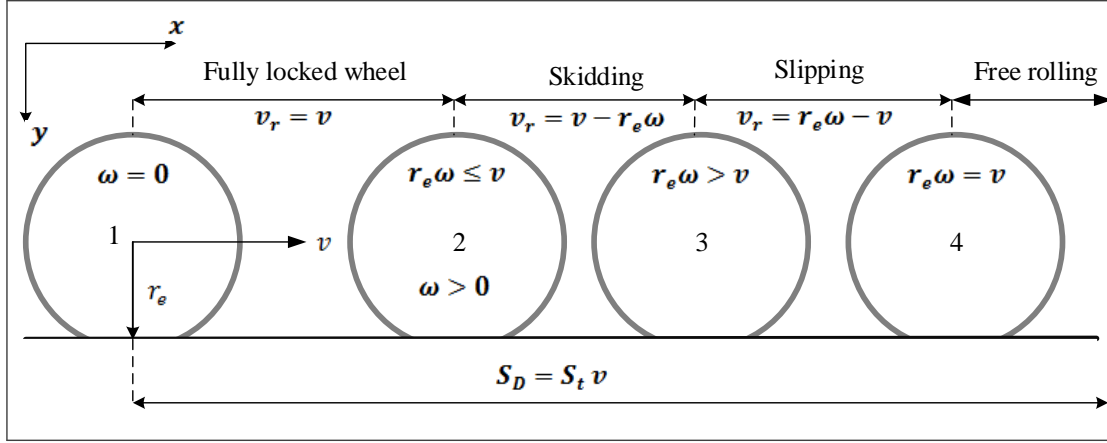


Fig. 3. Wheel dynamic at touchdown.

A fully locked wheel is the first stage; in this case,  $\omega = 0$ , and  $v_r = v$ . At second stage, the wheel starts to spin up to reach an equivalent translational speed,  $r_e \omega \leq v$ . In this case, the wheel is skidding and the relative speed will be as follows:

$$v_r = v - r_e \omega \quad (9)$$

At the third stage, the wheel is rolling more than its free rolling level,  $r_e \omega > v$ . The wheel is slipping, and the relative speed is:

$$v_r = r_e \omega - v \quad (10)$$

At the final stage, the wheel spins down to reach a steady state where,  $r_e \omega = v$  i.e. the skidding phase has ended, therefore, the relative speed is equal to zero as well as slip ratio. However, substituting Eqs. (9) and (10) in (8), the slip ratio Eq. will be as follows:

$$\lambda = \begin{cases} 1, & \omega = 0, & \text{locked wheel} \\ \frac{v - r_e \omega}{v}, & r_e \omega \leq v, & \text{skidding} \\ \frac{r_e \omega - v}{v}, & r_e \omega > v, & \text{slipping} \end{cases} \quad (11)$$

The wheel skidding distance,  $S_D$ , is a function of relative speed with respect to time, as follows:

$$S_D = \int v_r dt \quad (12)$$

Because constant horizontal speed is used; we can simply find the wheel skidding time,  $S_t$ , to be:

$$S_t = \frac{S_D}{v} \quad (13)$$

To estimate the friction between the tyre and runway, Burckhardt educed model for friction coefficient,  $\mu$  as a function of the wheel's longitudinal slip,  $\lambda$ , and aircraft landing speed,  $v$ , and is given by [24]:

$$\mu(v, \lambda) = [C_1(1 - e^{-C_2 \lambda}) - C_3 \lambda] e^{-C_4 \lambda v} \quad (14)$$

where,  $C_1$  is the maximum value of the friction curve,  $C_2$  is the shape of the friction curve,  $C_3$  is the difference between the maximum values at  $\lambda = 1$  and the friction curve, and  $C_4$  has value in the range of 0.02 – 0.04 s/m. In this model, dry concrete is used as runway and its parameters are:  $C_1 = 1.2801$ ,  $C_2 = 23.99$ ,  $C_3 = 0.52$ , and  $C_4$  assumed to be 0.03 s/m.

Fig. 4 shows  $\mu - \lambda$  curves with horizontal touchdown speed of 75.6 m/s. A constant friction coefficient of 0.65 was used, as many manufacturers use a constant friction coefficient based on the average value at slip in a range of  $\lambda = 0.05 - 0.15$ .

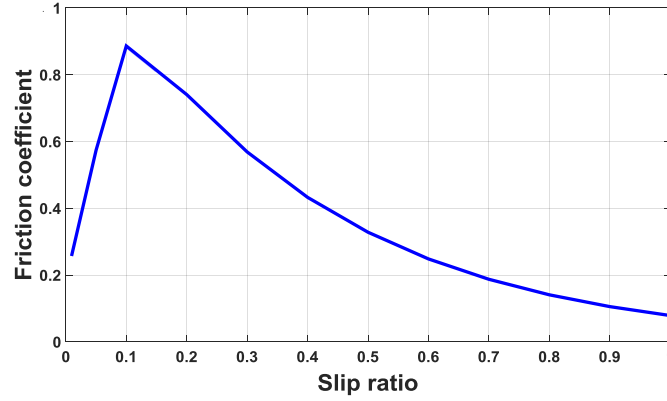


Fig. 4. Relationship between  $\mu$  and  $\lambda$  ( $v = 75.6$  m/s).

**Tyre Wear:** The Archard wear theory is a simple model to calculate the wear of slipping tyres, and is based on the theory of asperity contact. The abrasive wear is proportional to the force applying vertically on the contact zone, the sliding distance, and the wearing material's hardness [6]. In the Archard wear theory, the volume of tyre tread rubber eroded is defined as:

$$V = K_e \frac{F_R}{H} S_D \quad (15)$$

where,  $V$  is the total volume of wear amount ( $m^3$ ),  $K_e$  is the wear dimensionless coefficient "Archard's abrasion factor", which depends on the wear conditions, heavy or moderate, and is affected by the material's properties and its ability to wear. The value of  $K_e$  is less than 1 and it is in a range of  $10^{-8}$  and  $10^{-1}$  [5].  $H$  is the hardness of the softer material, which is the rubber in our case ( $N/m^2$ ).

Replacing  $S_D$  by  $\Delta t v_s$  for every time step and multiplying the rubber density by the two sides of Eq. (15) to calculate the wear mass to be as:

$$W_m = \rho K_e \frac{F_R}{H} \Delta t v_s \quad (16)$$

where,  $W_m$  is the wear amount (kg), and  $\rho$  is the rubber density ( $kg/m^3$ ).

The aircraft tyre generates heat that exceeds the rubber's critical temperature for about 0.1 seconds immediately after touchdown [2]. The tyre tread is always made of natural rubber and its critical temperature is about  $200^\circ C$  [2, 26, 27].

Increasing the temperature leads to an increase in the rubber's free volume which decreases the effective molecular conformations potential barriers; thus the network is weak and the hardness lessens [28]. The wear increases with a decrease in the material's hardness [2].

The rubber hardness is usually quoted in Shore hardness values, which range from zero to 100 and are calculated by an indentation test. These values are unit-less, but are related to the rubber's elastic modulus by various algorithms. Here, the hardness is converted to  $N/m^2$  to get wear volume in  $m^3$  as the force in (N) and sliding distance in (m) [29, 30]. Fig. 5 shows the rubber's hardness versus temperature. However, to avoid model complexity, the rubber hardness at its critical temperature was used.

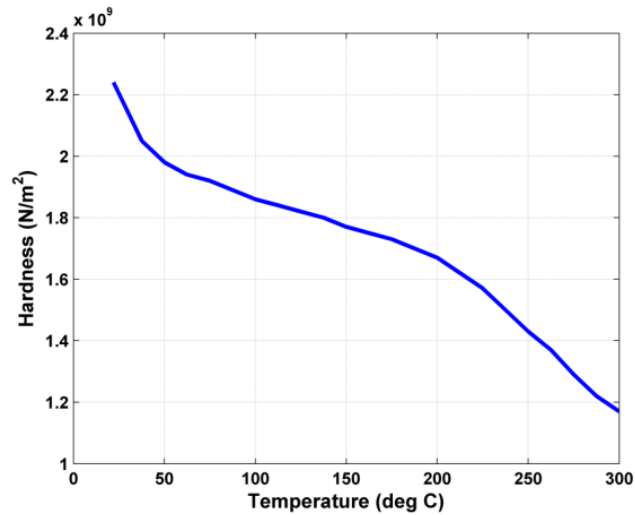


Fig. 5. Rubber hardness vs. temperature.

**Simulation Methodology:** The mass-spring-system has been modeled by ANSYS transient to simulate a drop test for the landing gear as shown in Fig. 6. The model simulates a typical aircraft landing using forward and vertical speeds plus gravity force.

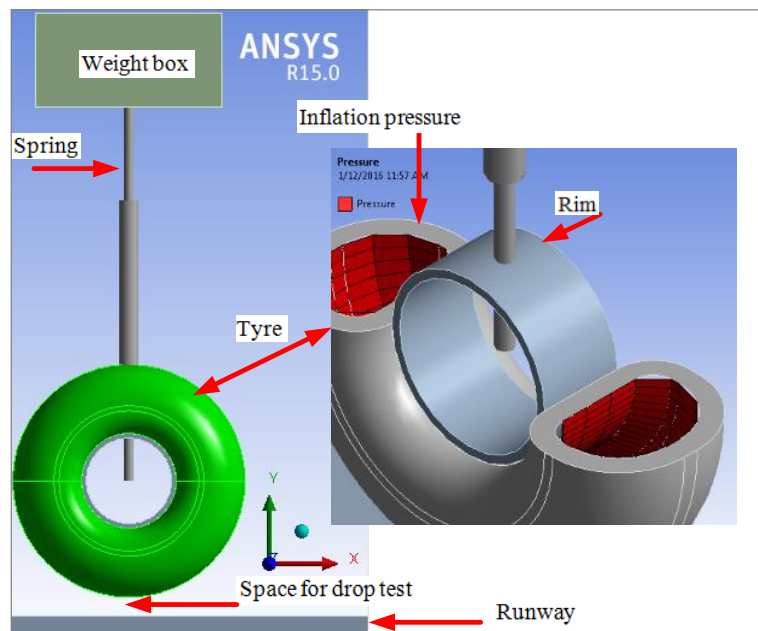


Fig. 6. Mass-spring-damper geometry by ANSYS.

The geometry modeled by the ANSYS design modeler consists of: wheel, spring, weight box, and soft concrete runway. The rim is added to the tyre to control the wheel's moment of inertia by increasing or decreasing its density to reach to the required weight, as the tyre density is not high enough. Table 1 shows the wheel data [31, 32].

Table 1 Wheel data.

	Weight (kg)	Radius (mm)	Width (mm)
Tyre	110	622.3	482.6
Rim	74.4	255	-----

The longitudinal spring connects the wheel centre with the weight box. This spring has the same data as a Boeing 747-400 main shock absorber (four oleo struts in parallel) divided by four to be valid for a single wheel. Thus, the spring linear stiffness is  $1.251.25 \times 10^6$  N/m, and the damping coefficient is  $1.37 \times 10^6$  Ns/m.

The tyre modeled simulates one made of hyper-plastic rubber material as the model focuses only on the first layer of the tread rubber. The tyre is modelled with enough thickness to stand a high load, filled to 215 PSI air pressure and meshed with 5180 nodes and 2286 elements. The Mooney- Rivlin material model is considered for the tyre rubber, because it has stress versus strain which helps to know the tyre failure level. Table 2 shows the tyre tread rubber properties [33].

Table 2 Tyre tread material parameters.

Properties	Value
Passion's ratio	0.49
Mass density ( $\text{kg/m}^3$ )	1125
Mooney Rivlin constants (Mpa)	$C_{10} = 0.643$ , $C_{01} = 0.824$

The maximum landing weight of a Boeing 747-400 is 295,743 kg; and applying on all the main landing gear wheels [19]. For this simulation, the weight box applied to one wheel is 18484 kg using heavy material with high density to reach to this value. However, there is wheel rotation or horizontal translational motion for every fraction of a second in this simulation. Therefore the time step is at the small value of  $dt = 1 \times 10^{-6} \text{ sec}$ .

## Results

The first simulation was for an initially static wheel, as in a typical landing. Fig. 7 shows the tyre deflection at the landing impact. The values of the pre-spinning wheel are chosen according to the wheel's angular velocity at steady state which is 121 rad/sec, and it is used to set the 100% and 50% pre-rolling wheel velocities.

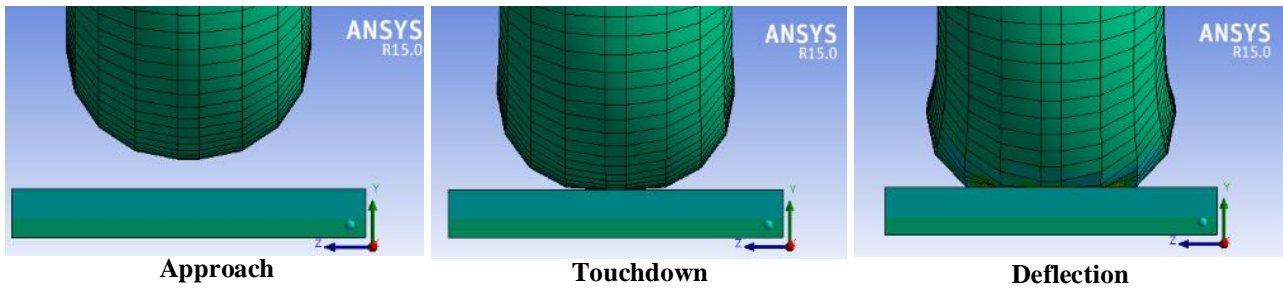


Fig. 7. Tyre deflection at landing impact.

**Friction and Reaction Forces:** The friction and reaction forces are the same for the three simulations, as the same speeds and vertical loads are used. The forces are shown in Fig. 8.

At touchdown, the friction is not enough to rotate the wheel, as the shock absorber is still compressing and absorbing the vertical load plus the aircraft sink rate. Within a fraction of a second, the shock absorber and the tyre are fully compressed, which leads to a significant increase in the friction force.



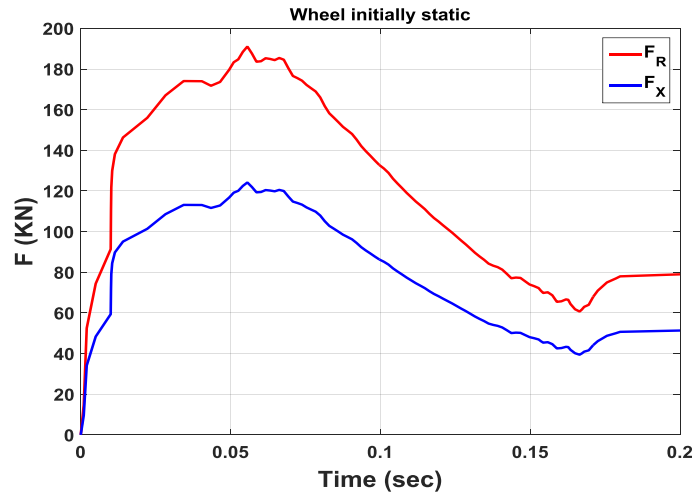


Fig. 8. Friction and reaction forces vs. time for a typical landing.

**Wheel Angular Velocities:** The friction force curve describes the wheel's angular speed behaviour. When the wheel touches the runway, the runway provides limited friction, which is not enough to spin it, so it is fully skidding as it pulled out by the aircraft forward speed while it is in stationary. Within fractions of a second, the friction increases dramatically to spin-up the wheel to overshoot level. Fig. 9 shows a comparison of the wheel's angular velocities.

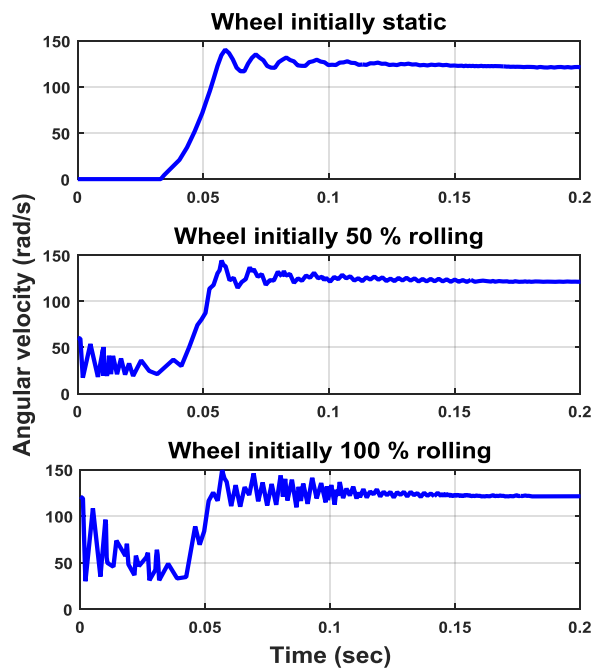


Fig. 9. Angular velocity of a wheel initially static, 50% and 100% pre-rotated vs. time.

All the simulations show the wheel spin-up overshooting, because the same friction force is affecting the wheel. So, if the wheel is already rolling the spin-up is higher, depending on the initial value of the rotation. The reason of overshoot level is that the wheel reaches to the free-rolling (equivalent to aircraft forward speed) before the peak value of friction force which is spin-up the wheel more.



The initially static wheel slid on the runway for 0.033 sec, covered 2.49 m to spin-up, overshoot and then wavered to reach a steady state within 0.12 sec, which agreed with the results shown by Besselink and khapane [9, 10].

When the wheel is pre-rotated at 50% and 100%, the fully-locked wheel is avoided, but the wheel shows a high drop of its angular speed immediately after touchdown. Fig. 10 shows the minimum and maximum velocities value for initially static and pre-spun wheels. Only rotation without torque applying on the wheel is used in this model; and this maybe the reason for the high reduction in rotation.

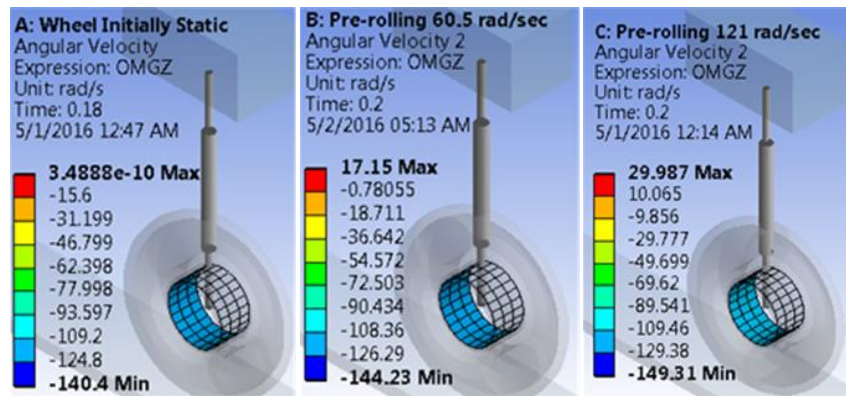


Fig. 10. maximum and minimum wheel angular velocities

**Tyre Wear:** Fig. 11 shows a comparison of tyre wear for a typical landing, for 50% and 100% pre-rotated wheels. Most of wear on rubber of a typical landing occurred during the fully locked wheel phase and then fluctuated to be about zero at the end of the skid phase. The peak value is 3.39 grams after 0.04 sec, which occurred at high slip and friction force. At the peak value of friction force, the wear is less, as the wheel has already start to rotated due to the friction which means a lower skidding speed.

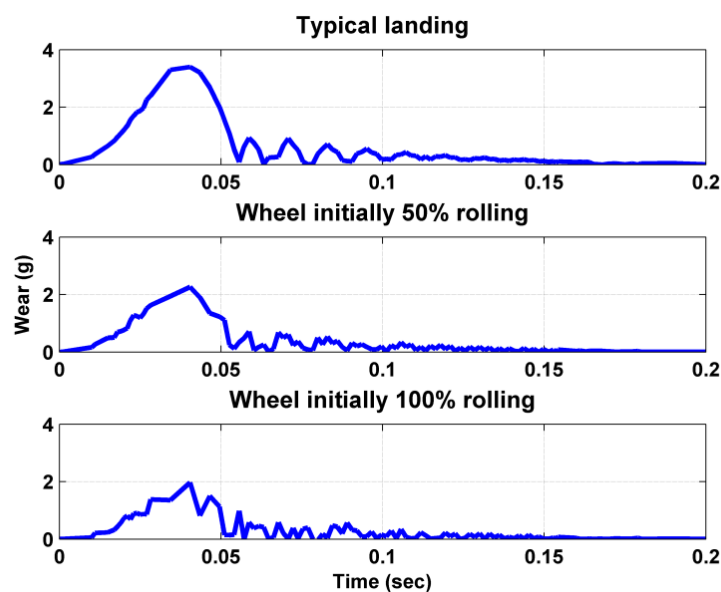


Fig. 11. Wear of tyre initially static, 50%, and 100% pre-rotated vs. time

The 50% and 100% pre-rotated wheels shows a maximum wear of 2.26 grams and 1.97 grams respectively, which occurred after 0.04 sec. The maximum wear for the three simulations occurred at the same time with different values; this is because the reaction force is similar, but the skidding speed is different.

A comparison of the total wear is shown by Fig. 12. The total wear of the static wheel is 58.32 grams; and multiplying this value by the total number of landing gear wheels gives 933.1 grams. This value is high because the aircraft MLW is used on all the wheels. However, this value agreed with the results found by Bennett et al [3].

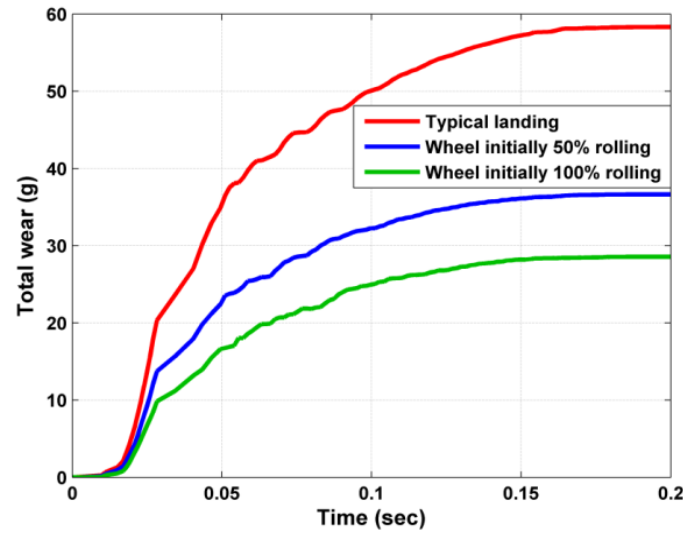


Fig. 12. Total wear of tyre initially static, 50% and 100% pre-rotated vs. time.

**Summary of Results:** Table 3 shows the results summary which includes: the initial wheel angular velocity ( $\omega_i$ ), maximum (Max. $\omega$ ) and minimum (Min. $\omega$ ) wheel angular velocity achieved; the fully locked wheel distance and time; the wheel spin-up or down distance and time (this is when the wheel starts to rotate until it reaches a steady rolling level); the total skidding distance and time (which is measured from the first contact of the tyre with the runway until the end of the skidding phase); the maximum slip ratio achieved; the total rubber eroded (total wear) and the percentage of the total wear reduction compared to the total tyre wear for a typical landing.

Table 3. Results summary

$\omega_i$	Max.	Min.	Fully locked wheel distance	Fully locked wheel time	Total skidding distance	Total skidding Time	Max. Slip ratio	Total wear	Comparison to a typical landing
(rad/sec)	$\omega$ (rad/sec)	$\omega$ (rad/sec)	(m)	(sec)	(m)	(sec)		(grams)	%
0	140.4	0	2.49	0.033	9.1	0.12	1	58.32	-----
60.5	144.23	17.15	0.0	0.0	9.83	0.13	0.86	36.64	- 37
121	149.3	30.0	0.0	0.0	10.58	0.14	0.75	28.56	-51

## Conclusion

A single wheel of an aircraft's main landing gear was modeled as a mass-spring-system to simulate the landing. ANSYS transient was used to compare the tyre wear in a typical landing and when the wheel was pre-rotated before touchdown. The wear calculation was based on the Archard theory. The results show that tyre wear still occurred even with a 100% pre-rotated wheel, because the wheel angular velocity drops immediately after touchdown, which increases the slip thus incurred. When the wheel is initially rotated at 50% and 100% of its free-rolling; the total tyre rubber wear is reduced by 37% and 51% respectively, which could improve the tyre's life. In the future work, further research should estimate the effect of a pre-rotating wheel on the reduction of heat generated by the skidding tyre.

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